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Droplet Characteristics and Near Nozzle Dispersion of Cold and Thermal Fog

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ABSTRACT: In an effort to improve application methods for controlling sand flies in desert environments, a hand-held ultra-low volume (ULV) aerosol generator, a truck-mounted ULV aerosol generator, and a hand-held thermal fogger were evaluated. The velocity and temperature of the air and characteristics of droplets generated by these aerosol generators were measured at various distances from the nozzle. The droplet size characteristics were measured for three flow rates each of BVA-13 mineral oil and a mixture of water and nonionic surfactant with a phase Doppler particle analyzer. Moving 0.9 m away from the nozzle, the velocity of air produced by the two hand-held sprayers decreased to <5 m/s, whereas the truck-mounted sprayer still had an air velocity of 15 m/s. The air produced by truck-mounted cold fogger, thermal fogger, and hand-held ULV applicator was 38, 49.2, and 8.5°C above ambient temperature, respectively. Increases in flow rate, generally, did not affect the droplet size for the two hand-held units; however the droplet size increased as the flow

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14. ABSTRACT
In an effort to improve application methods for controlling sand flies in desert environments, a hand-held ultra-low volume (ULV) aerosol generator a truck-mounted ULV aerosol generator, and a hand-held thermal fogger were evaluated. The velocity and temperature of the air and characteristics of droplets generated by these aerosol generators were measured at various distances from the nozzle. The droplet size characteristics were measured for three flow rates each of BVA-13 mineral oil and a mixture of water and nonionic surfactant with a phase Doppler particle analyzer. Moving 0.9 m away from the nozzle, the velocity of air produced by the two hand-held sprayers decreased to <5 m/s, whereas the truck-mounted sprayer still had an air velocity of 15 m/s. The air produced by truck-mounted cold fogger, thermal fogger and hand-held ULV applicator was 38, 49.2, and 8.5 C above ambient temperature respectively. Increases in flow rate, generally, did not affect the droplet size for the two hand-held units; however the droplet size increased as the flow rate increased on the truck- mounted sprayer. For all three aerosol generators droplet concentration increased with increasing flow rates. Both ULV generators showed an increase in droplet size and a decrease in droplet concentration as the distance from nozzle increased. However, the droplet size decreased and the droplet concentration increased when applied using the thermal fogger.

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rate increased on the truck- mounted sprayer. For all three aerosol generators, droplet concentration increased with increasing flow rates. Both ULV generators showed an increase in droplet size and a decrease in droplet concentration as the distance from nozzle increased. However, the droplet size decreased and the droplet concentration increased when applied using the thermal fogger.

KEYWORDS: mosquitoes, sand fly, space spraying, vector control, warfighter protection

Introduction

One of the research objectives of the Deployed War-Fighter Protection Program (DWFP) is to develop new or to improve existing pesticide application technologies for increasing efficiency of pesticide-dispersal techniques and/or to reduce the amount of active ingredient needed for effective pest control. Space spray is defined as a spray for the control of insects in flight by insecticides dispersed into the atmosphere [1] or into a volume of air above the surface of the earth, called the insect zone. For effective control of flying mosquitoes and sand flies, droplets in a space spray should be thoroughly dispersed and remain suspended in the insect zone as long as possible. Droplets in ultra-low volume (ULV) sprays generated with cold or thermal foggers have the potential to meet these requirements because of their size and expected interaction with the environment. However, the efficacy of ULV sprays for controlling sand flies has been inconsistent. For example, truck-mounted ULV sprayers commonly used for mosquito control [2] have been largely ineffective when used to control sand flies in Iraq [3], whereas a similar ULV sprayer has shown excellent control of sand flies in Kenya [4]. These conflicting results may be associated with the inappropriate use of the sprayer and highlight the need to better understand ULV spray applications.

According to Dodd [1], the mechanism of ULV pesticide delivery and dispersion has not been investigated thoroughly in spite of extensive use of space sprays. Several researchers [1,5,6] reported on the effectiveness of indoor space sprays, but additional information is needed on the performance of outdoor applications. Alexander and Maroli [7] discussed many control practices for sand flies in various parts of the world and found that residual sprays, which leave deposits on surfaces where insects may rest or sit, are effective in urban areas with high concentrations of sand flies. However, deployed service members often operate in rural areas, where residual sprays are impractical because of widely dispersed dwellings [7], high temperatures, strong radiation, and dust [8]. Thus, space spraying seems to be the only viable option [7,9].

For successful space spraying, it is necessary to know the role of various parameters that influence the generation, dispersion, and deposition of droplets. A comprehensive understanding of these mechanisms is essential for improving the efficiency of ULV/aerosol sprays and fogging applications. We are not aware of any research in this area that has been carried out in a military environment, although agricultural sprays have been studied extensively [10–16].

Efforts to improve application methods for effective control of sand flies in military desert environments were initiated through the DWFP program with a focus on improving the efficiency of pesticide applications. The overall objective of this project was to investigate the effect of droplet parameters on transport and dispersal of aerosol droplets generated by various application technologies. Ultimately, this information could be used to improve the efficiency of aerosol spray delivery and, hence, the efficacy of sand fly control in desert environments. The specific objective of this work was to study the effect of application parameters of ULV aerosol generators and foggers on spray characteristics, transport, and dispersion near the nozzle.

Materials and Methods

Equipment

Three types of applicators were evaluated in this study: a hand-held ULV applicator, a hand-held thermal fogger, and a truck-mounted ULV sprayer

FIG. 1—*Aerosol applicators used in the study.*

(Fig. 1). The hand-held ULV sprayer (Fig. 1(*a*)) was a Colt ULV Aerosol Generator (London Fog, Inc., Long Lake, MN) that is powered by a 1.49-kW gasoline engine and uses an air-shear nozzle and changeable disks to set the flow rate (0–118 ml/min). The sprayer has a net weight of 8.6 kg and formulation and fuel tanks have 1-l capacity. During our experiments, the disk no. 16, 22, and 24 were installed to deliver flow rates of 30, 55, and 60 mL/min, respectively.

The hand-held thermal fogger was a Curtis Dyna-Fog Golden Eagle (Model 2610, Curtis Dyna-Fog Ltd, Westfield, IN) that uses a gasoline powered 22-kW resonant pulse-jet engine to produce thermal fog (Fig. 1(*b*)). This thermal fogger has a net weight of 9 kg, a tank capacity of 4.2 l and a maximum flow rate of 606 ml/min selected with a dial scaled 1–10. The dial was set at 2, 6, and 10 in our experiment to give flow rates of 177, 518, and 606 ml/min, respectively.

The truck-mounted ULV sprayer was a London Fog 18–20 aerosol generator (London Fog Inc, Long Lake, MN) that is powered by a 13.2-kW gasoline engine and equipped with an air-shear nozzle (Fig. 1(*c*)). The source of air is a rotary, positive-displacement blower with an air flow capacity of 10.1 m^3/min. The nozzle could be rotated 360°, both horizontally and vertically. The sprayer weighs 202 kg, has a 56-l spray tank, a 1.6-l flush tank, and can have flow rates up to 650 ml/min selected by adjusting the pump displacement. This sprayer was operated to deliver 118, 355, and 591 ml/min of spray in this experiment.

Data Collection

The velocity and temperature of the air generated by these sprayers were measured at various distances from the nozzle using a hot-wire anemometer (Veloci-Calc Model 9555 P, TSI Inc. Shoreview, MN) and an infrared thermometer (Model Minitemp, Raytek Corporation, Santa Cruz, CA), respectively. The local ambient temperature was also recorded with the same thermometer. These measurements were taken in a protected space in front of the building during relatively calm conditions. A 2D phase Doppler particle analyzer (PDPA) system (TSI Inc., Shoreview, MN) was used to characterize the droplet spectra. For this study, the PDPA transmitter and receiver had 500- and 300-mm lenses, respectively. This resulted in measurable droplet size range of 0.6–211 μm. Droplet characteristics, such as droplet volume distribution and droplet concentration, were calculated by the PDPA software. Droplet volume distribution is represented by volume median diameter (VMD or $D_{V0.5}$), $D_{V0.1}$, and $D_{V0.9}$. The $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$, are the droplet diameters such that 10 %, 50 %, and 90 % of the spray volume, respectively, is contained by droplets smaller than these sizes. Droplet concentration is defined as the number of droplets per unit volume of air (#/cm^3). Using the volume of VMD, the droplet concentration was converted to spray volume concentration (ml/m^3), onward referred to as spray volume.

The droplet size measurements were made inside the laboratory with door open to discharge spray cloud toward that door. For both ULV sprayers, the

spray clouds were characterized using two spray liquids: (1) BVA-13 mineral oil (specific gravity (sp. gr.) = 0.8493, Adapco Inc., Sanford, FL.), and (2) a 99.8 + 0.2 by volume mixture of water and a non-ionic surfactant (R-11, sp. gr. = 1.02, Wilbur Ellis Co., San Antonio, TX), and only BVA oil was used for the thermal fogger. The measurements were made at 0.3, 0.9, and 1.5 m from the nozzle outlet using flow rates listed earlier, selected to cover an available range for each applicator. For each of the truck-mounted sprayer and thermal fogger, an additional measurement was made at distances of 2.4 and 0.04 m, respectively. Each characterization was replicated three times. For each measurement, the spray was released in the horizontal direction and measurements were taken at the horizontal center of the spray plume. The spray cloud was scanned vertically from top to bottom in a sweep (continuous capture) mode of the PDPA. Based on the distance from the sprayer nozzle, the scan ranged from 25 to 60 cm in the vertical direction (Fig. 2).

Individual analysis of variance was performed using JMP statistical software version 5 (JMP, Cary, NC) for each piece of equipment. Therefore, comparisons between aerosol generators were not performed. For each applicator, the analysis of variance was performed to find the effect of spray liquids, distances and flow rates on droplet size characteristics, droplet concentration, and spray volume. The effect of flow rate on these parameters was also analyzed within each combination of spray liquid and distance and means were

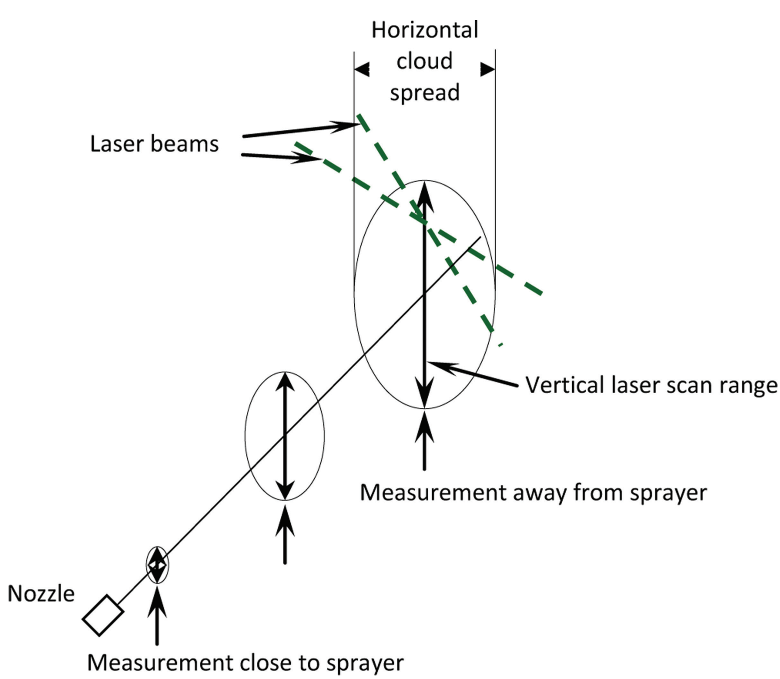

FIG. 2—*Schematic of droplet size measurement locations.*

compared using the *t* test at a 95 % level of confidence. Functions to various data sets were fit with Microsoft Excel 2007.

Results

Air Velocity and Temperature

The velocity of the air produced by the three sprayers decreased with increasing distance from the nozzle (Fig. 3). Air velocity from the truck-mounted sprayer was highest near the exit and was approximately 15 m/s at 0.9 m away from the nozzle. The two hand-held units produced lower velocities at the nozzle outlet, which reduced to <5 m/s at 0.9 m from the nozzle. The ambient temperatures at the time of measurements were 5.7, 17.8, and 20.9°C for the truck-mounted cold fogger, thermal fogger, and hand-held ULV applicator, respectively. At the nozzle outlet, the truck-mounted ULV sprayer, the hand-held thermal fogger, and the hand-held ULV applicator generated air 38, 49.2, and 8.5°C warmer, respectively, than the ambient air. The temperature of air

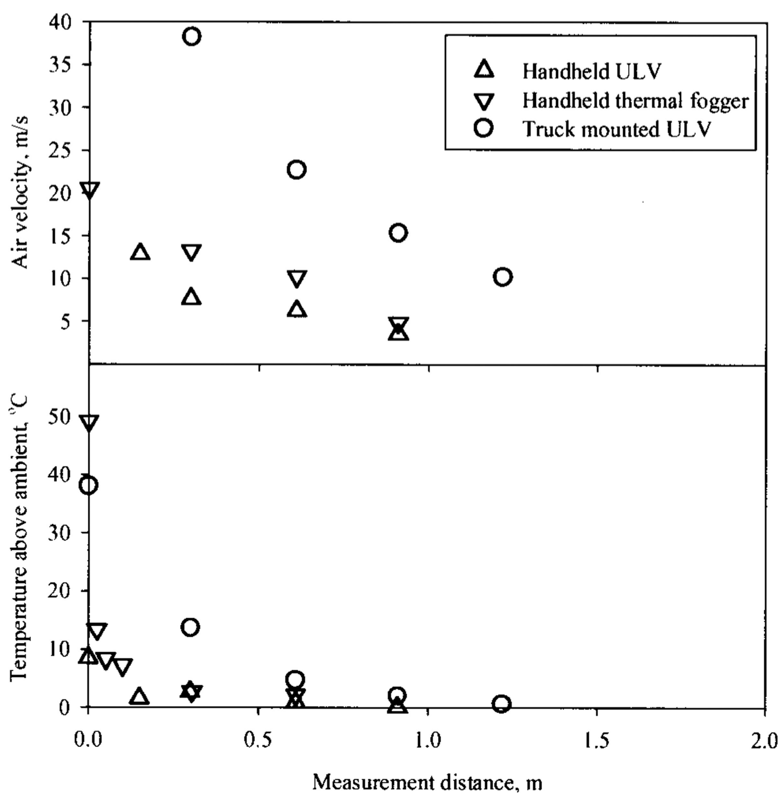

FIG. 3—*Air velocity and temperature at various distances from the nozzle.*

from all three applicators reached ambient conditions at 0.9–1.2 m away from the nozzle outlet (Fig. 3).

Droplet Size Characteristics

The data for droplet size characteristics are presented in Tables 1–3 for hand-held ULV sprayer, truck-mounted ULV sprayer, and hand-held thermal fogger, respectively. Overall, the increase in flow rate from hand-held ULV sprayer did not have a consistent effect on $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$ (Table 1). At all distances, droplets were smaller for oil than water + NIS spray, probably because of the lower density of the oil. Application of BVA-13 oil produced ULV droplets at VMD of 21–28 μm, whereas water + NIS droplets were larger than the ULV range (VMD <30 μm for ULV [17]) and VMDs were from 33–40 μm (Table 1). Increasing the flow rate did not affect droplet size except significantly higher $D_{V0.9}$ at highest flow rate of water + NIS, and thus the droplet concentration and spray volume increased with the increased flow rate (Fig. 4). The increased droplet concentration enhances the probability of droplets coming in contact with insect. It should be noted that the rate of increase in droplet concentration was different for oil and water + NIS droplets (Fig. 4) but the spray volume of oil had similar trend as the droplet concentration. For water + NIS droplets, the spray volume changed with increasing distance rapidly compared to the droplet concentration change (Fig. 4), which could be because of the increase in VMD and $D_{V0.9}$ with flow rate (Table 1). As the distance from the sprayer increased, the $D_{V0.1}$ and $D_{V0.5}$ of the oil spray increased, whereas the $D_{V0.9}$ decreased (Table 1). This indicates that span of the droplet spectrum decreased with increasing distance from the nozzle outlet because of faster evaporation, and disappearance of smaller droplets compared to larger ones.

For the truck-mounted ULV sprayer, water + NIS droplets, in general, were larger than oil droplets and this difference was significant in case of $D_{V0.5}$ and $D_{V0.9}$ (Table 2). All the droplet size statistics ($D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$) increased significantly with increasing flow rate (Fig. 5). The rate of change was lowest for $D_{V0.1}$ and increased with increasing droplet size percentile. The water + NIS and oil had a similar $D_{V0.1}$, whereas the water + NIS application resulted in a higher $D_{V0.5}$ and $D_{V0.9}$. The increase in droplet size is largely because of a reduction in kinetic energy in the air available to atomize a unit volume of the liquid when the flow rate is increased at a constant air flow. This effect did not show in hand-held ULV applicator because of limited range of available flow rates. As the two spray liquids have different densities (water + NIS 0.998 g/mL; oil 0.845 g/mL), their densities were used to convert the volume flow rate (mL/min) into mass flow rate (g/min). Plotted against mass flow rate, the means of droplet size parameters for the two liquids sprayed through this sprayer collapsed to a single curve (Fig. 6). The three regressions

TABLE 1—*Droplet characteristics of hand-held ULV sprayer.*

Spray liquid	Distance from nozzle (m)	Flow rate (ml/min)	Mean ± standard deviation				
			$D_{V0.1}$ (μm)	$D_{V0.5}$ (μm)	$D_{V0.9}$ (μm)	Droplet concentration (No./cm^3)	Spray volume (ml/m^3)
BVA-13 oil	0.3	30	16.2 ± 0.3 a	24.5 ± 1.2 a	45.4 ± 12.0 a	1798 ± 319 b	13.9 ± 2.6 b
		55	12.4 ± 0.6 c	21.4 ± 1.3 b	43.3 ± 17.2 a	2063 ± 840 b	10.1 ± 2.5 b
		60	14.3 ± 0.9 b	22.9 ± 1.8 a,b	59.7 ± 38.3 a	8551 ± 5076 a	49.2 ± 23.7 a
	0.9	30	15.0 ± 1.4 a	25.8 ± 1.8 a	44.6 ± 1.4 a	1835 ± 545 a	16.3 ± 4.3 a
		55	14.9 ± 0.7 a	26.7 ± 3.3 a	43.7 ± 6.6 a	2617 ± 1449 a	23.3 ± 8.1 a
		60	16.4 ± 1.3 a	24.5 ± 1.8 a	36.0 ± 4.2 a	2619 ± 669 a	21.2 ± 9.9 a
	1.5	30	18.6 ± 2.9 a	28.3 ± 4.1 a	43.7 ± 13.4 a	889 ± 612 a	12.6 ± 11.4 a
		55	16.2 ± 3.9 a	24.7 ± 3.5 a	42.5 ± 11.6 a	1478 ± 853 a	10.3 ± 4.7 a
		60	16.7 ± 1.7 a	26.1 ± 2.2 a	40.2 ± 6.0 a	1030 ± 203 a	9.7 ± 3.3 a
Water + NIS[a]	0.3	30	20.2 ± 1.0 a	34.3 ± 4.3 a	54.0 ± 13.0 a	955 ± 322 b	20.5 ± 10.3 b
		55	20.7 ± 1.0 a	34.4 ± 0.6 a	55.9 ± 3.5 a	1737 ± 371 a	37.4 ± 10.1 a,b
		60	21.7 ± 0.5 a	36.6 ± 1.8 a	59.3 ± 11.6 a	1896 ± 318 a	49.8 ± 14.9 a
	0.9	30	20.8 ± 0.5 a	33.1 ± 2.8 a	49.4 ± 3.8 c	1197 ± 229 a	23.3 ± 8.7 a
		55	21.2 ± 0.5 a,b	35.6 ± 2.4 a	58.3 ± 1.8 b	1469 ± 125 a	35.1 ± 9.2 a
		60	22.1 ± 0.5 a	38.2 ± 3.4 a	73.2 ± 4.0 a	1498 ± 533 a	41.8 ± 10.6 a
	1.5	30	22.4 ± 2.8 a	39.1 ± 6.6 a	55.4 ± 6.8 a	891 ± 241 a	26.7 ± 6.1 a
		55	21.8 ± 3.8 a	35.3 ± 7.3 a	48.8 ± 15.6 a	1107 ± 734 a	32.8 ± 36.7 a
		60	23.1 ± 2.0 a	39.5 ± 4.6 a	57.5 ± 15.3 a	1036 ± 447 a	36.6 ± 27.2 a

Note: Means for flow rate in a column for each set of spray liquid and distance having different letters are significantly different (*a* 0.05).
[a]Non-ionic surfactant.

TABLE 2—*Droplet size characteristics of truck-mounted ULV sprayer.*

			Mean ± standard deviation				
Spray liquid	Distance from nozzle (m)	Flow rate (ml/min)	$D_{V0.1}$ (μm)	$D_{V0.5}$ (μm)	$D_{V0.9}$ (μm)	Droplet concentration (No./cm$^{3)}$)	Spray volume (mL/m$^{3)}$)
BVA-13 oil	0.3	118	9.9 ± 0.0 c	14.5 ± 0.0 c	19.9 ± 0.1 c	515 ± 58 c	0.8 ± 0.1 c
		355	12.0 ± 0.1 b	17.7 ± 0.2 b	24.4 ± 0.2 b	1115 ± 81 b	3.2 ± 0.3 b
		591	13.2 ± 0.3 a	19.3 ± 0.3 a	26.5 ± 0.5 a	1430 ± 79 a	5.4 ± 0.4 a
	0.9	118	10.5 ± 0.6 b	14.2 ± 0.4 b	18.7 ± 0.8 b	189 ± 25 b	0.3 ± 0.0 c
		355	14.7 ± 1.5 a	21.1 ± 2.0 a	31.9 ± 4.6 a	385 ± 193 a,b	1.6 ± 0.5 b
		591	15.0 ± 0.8 a	22.6 ± 1.6 a	37.3 ± 10.0 a	522 ± 146 a	3.1 ± 0.2 a
	1.5	118	11.1 ± 0.6 b	15.1 ± 0.7 c	22.0 ± 2.7 c	183 ± 69 a	0.3 ± 0.1 a
		355	14.8 ± 1.0 a	20.7 ± 1.0 b	27.7 ± 0.8 b	171 ± 88 a	0.8 ± 0.3 a
		591	15.8 ± 0.1 a	22.7 ± 0.1 a	30.5 ± 0.3 a	130 ± 66 a	0.8 ± 0.4 a
Water + NIS[a]	0.3	118	10.2 ± 0.1 c	16.7 ± 0.1 c	25.6 ± 0.2 c	495 ± 43 b	1.2 ± 0.1 c
		355	12.3 ± 0.4 b	20.6 ± 0.1 b	33.1 ± 1.7 b	2178 ± 191 a	10.0 ± 0.8 b
		591	14.6 ± 0.7 a	23.8 ± 0.6 a	38.4 ± 1.2 a	2015 ± 505 a	14.0 ± 2.4 a
	0.9	118	10.4 ± 0.1 b	16.5 ± 0.4 b	24.4 ± 0.4 c	242 ± 35 c	0.6 ± 0.1 b
		355	11.5 ± 1.2 a,b	19.3 ± 2.7 a,b	29.4 ± 4.2 b	578 ± 276 b	2.5 ± 1.7 b
		591	12.6 ± 0.2 a	21.6 ± 0.1 a	34.4 ± 0.3 a	1117 ± 55 a	5.9 ± 0.3 a
	1.5	118	11.3 ± 0.6 b	17.2 ± 0.7 b	25.2 ± 0.9 b	307 ± 22 b	0.8 ± 0.1 b
		355	13.6 ± 0.1 a	22.3 ± 0.2 a	34.2 ± 0.4 a	674 ± 72 a	3.9 ± 0.5 a
		591	13.8 ± 0.1 a	23.0 ± 0.4 a	36.0 ± 1.2 a	729 ± 111 a	4.7 ± 0.9 a
	2.4	118	11.5 ± 0.1 c	17.4 ± 0.2 c	25.0 ± 0.5 c	191 ± 5 c	0.5 ± 0.0 b
		355	14.2 ± 0.2 b	22.6 ± 0.1 b	34.0 ± 0.9 b	420 ± 78 a	2.5 ± 0.4 a
		591	16.1 ± 0.8 a	25.2 ± 0.9 a	36.7 ± 1.3 a	317 ± 63 b	2.6 ± 0.4 a

Note: Means for flow rate in a column for each set of spray liquid and distance having different letters are significantly different (*a* 0.05).
[a]Non-ionic surfactant.

TABLE 3—*Droplet size characteristics of hand-held thermal fogger.*

Distance from nozzle (m)	Approximate flow rate of BVA-13 oil (ml/min)	Mean ± standard deviation				
		$D_{V0.1}$ (μm)	$D_V0.5$ (μm)	$D_V0.9$ (μm)	Droplet concentration (No./cm^3)	Spray volume (ml/m^3)
0.04	177	4.6 ± 0.7 a	16.5 ± 5.7 a	27.5 ± 7.8 a	3101 ± 982 a	11.1 ± 13.8 a
	518	4.6 ± 3.0 a	19.1 ± 5.7 a	31.9 ± 5.0 a	3894 ± 3176 a	11.0 ± 12.2 a
	606	3.4 ± 1.7 a	13.1 ± 5.9 a	24.7 ± 3.5 a	7733 ± 6501 a	5.9 ± 2.6 a
0.3	177	3.9 ± 1.2 a	11.7 ± 4.1 a	25.3 ± 6.9 a	1676 ± 1632 b	1.1 ± 0.7 a
	518	2.5 ± 0.5 a,b	12.3 ± 10.1 a	28.1 ± 2.1 a	7109 ± 5311 a,b	6.7 ± 9.3 a
	606	2.1 ± 0.3 b	10.1 ± 7.0 a	28.9 ± 8.6 a	11452 ± 2645 a	9.8 ± 13.7 a
0.9	177	2.2 ± 0.1 a	5.6 ± 0.5 a	26.9 ± 1.3 a	10167 ± 8238 a	1.1 ± 1.2 a
	518	2.0 ± 0.1 a	5.0 ± 0.4 a	19.8 ± 8.3 a	8717 ± 7296 a	0.5 ± 0.4 a
	606	1.8 ± 0.2 b	4.3 ± 1.2 a	16.2 ± 11.7 a	12951 ± 994 a	0.6 ± 0.6 a
1.5	177	2.0 ± 0.2 a	4.9 ± 1.1 a	20.6 ± 3.9 a	6721 ± 3840 a	0.3 ± 0.1 a
	518	1.7 ± 0.0 a	3.6 ± 0.2 a	18.1 ± 3.0 a	9003 ± 1009 a	0.2 ± 0.0 a
	606	1.8 ± 0.1 a	4.0 ± 0.5 a	22.4 ± 11.7 a	14148 ± 8337 a	0.5 ± 0.2 a

Note: Means for flow rate in a column for each distance having different letters are significantly different (*a* 0.05).

explained 76 %, 91 %, and 86 % of variability in the data for $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$, respectively. The rate of change in droplet statistics ($D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$) with mass flow rate increased for higher droplet size percentiles. This trend indicates that not only the droplet size increases with an increase in mass

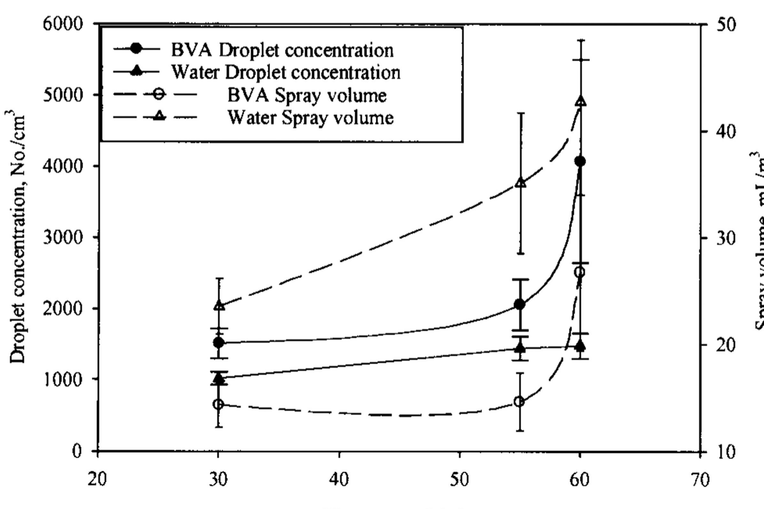

FIG. 4—*Line plots showing droplet concentration and spray volume at different flow rates of the hand-held ULV sprayer.*

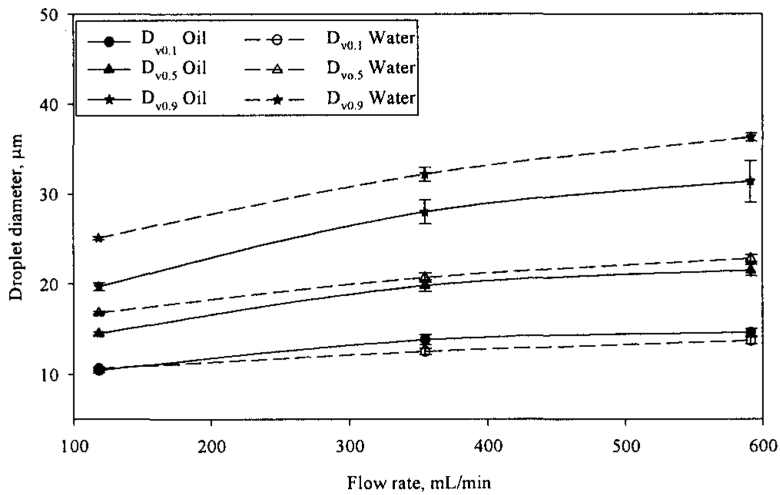

FIG. 5—*Line plots showing the effect of flow rate (FR) on droplet size characteristics of oil and water + NIS sprays from truck-mounted ULV sprayer. Functions (not plotted here) for these plots are: BVA-13 oil:* $D_{V0.1} = 0.0089FR + 9.8$; $D_{V0.5} = 0.0148FR + 13.4$; $D_{V0.9} = 0.0247FR + 17.6$; *water + NIS:* $D_{V0.1} = 0.0060FR + 9.9$; $D_{V0.5} = 0.0127FR + 15.6$; $D_{V0.9} = 0.0237FR + 22.8$.

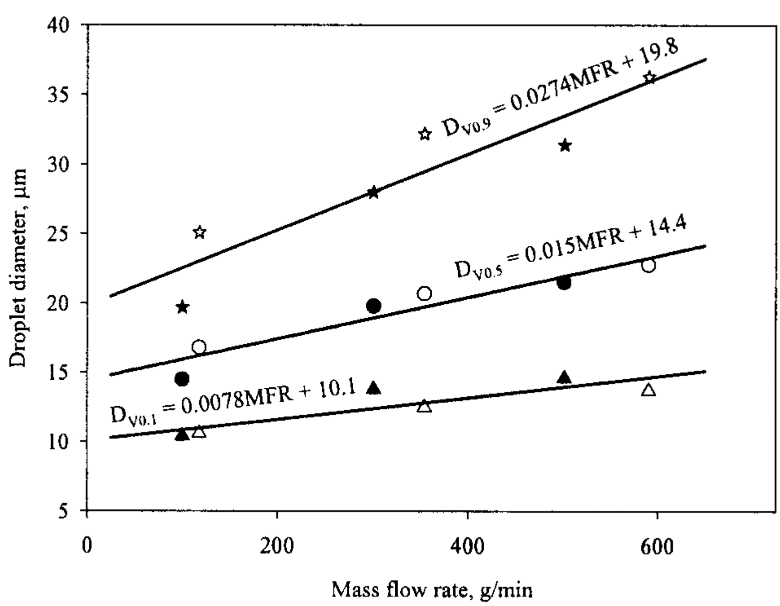

FIG. 6—*Effect of mass flow rate (MFR) on droplet size for truck-mounted sprayer. Lines show fitted functions, filled symbols represent oil, and open symbols represent water + NIS.*

flow rate, but the droplet spectrum also widens. The data analysis indicated that droplet concentration and spray volume mostly increased with the increase in flow rate.

The droplet size characteristics for the truck-mounted ULV sprayer were significantly affected by the distance from the nozzle. On average, all three parameters ($D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$) increased with increasing distance (Fig. 7). This increase could be attributed to rapid evaporation of smaller droplets with distance from the sprayer compared to the larger droplets. Droplet concentration and spray volume decreased with increase in distance for oil and water + NIS sprays (Table 2). This decrease can be attributed mainly to spray dispersion, but also to a difference in evaporation rate of smaller and larger droplets.

For the hand-held thermal fogger, droplet size was largely unaffected by the flow rate (Table 3), but decreased significantly as the distance from the sprayer increased (Fig. 8). The droplet concentration increased with increasing flow rate at all distances (Table 3). It also increased with increasing distance from the nozzle outlet (Fig. 8), which is not expected. On the contrary, the spray volume, a parameter representing the combined effect of VMD and droplet concentration, decreased significantly with increased distance from the fogger outlet. The decrease in spray volume, as expected, can be attributed to the dispersion of the droplets into a larger area as the droplets move away from the fogger. This trend makes one think that there is some sort of breakup of the

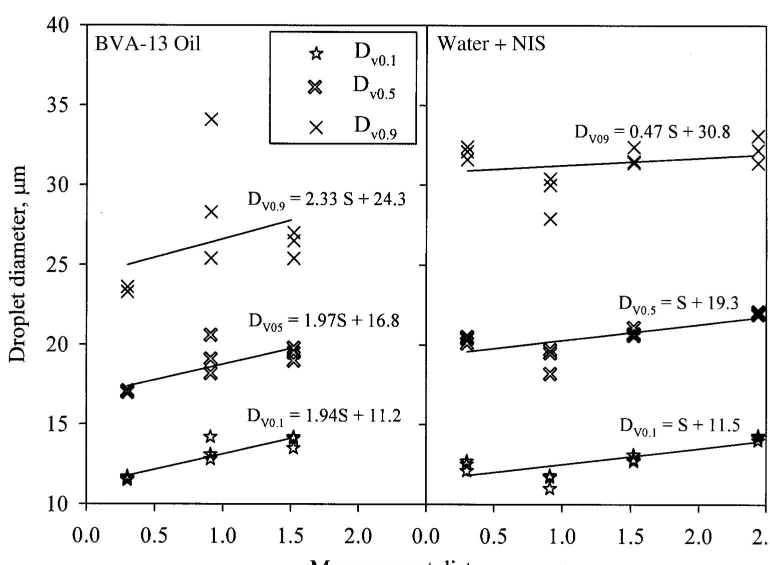

FIG. 7—*Change in droplet size with distance (S) from nozzle of truck mounted sprayer. Lines represent fitted functions.*

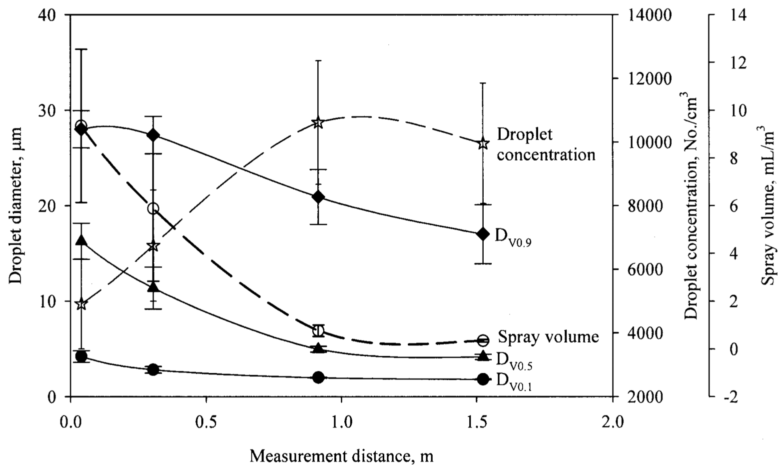

FIG. 8—*Droplet statistics, droplet concentration, and spray volume at different distances from hand-held thermal fogger. (Lines are drawn between data for clarity.)*

larger droplets in to smaller ones as they are propelled from the fogger outlet and rapidly cool down.

Discussion

The study has several findings that are beneficial for pest management professionals and spray application personnel. It was noted that cold foggers can also generate a considerable amount of heat in the air stream produced (Fig. 3). This may have implications on droplet generation and on the chemical stability of pesticide formulations ultimately affecting efficacy [18,19]. Therefore, the temperature of the air generated and any temperature limits on pesticide labels should be considered when selecting a combination of equipment and pesticide.

In today's spray applications, the flow rate is changed proportionally to travel speed to keep the application rate constant. This study demonstrates that droplet size can change with the flow rate. This implies that the change in number of droplets generated will not always be proportional to the flow rate, which was shown for all three sprayers tested (Tables 1–3, Fig. 4). Furthermore, droplet concentration normalized for flow rate will decrease with increasing travel speed. Ultimately, the change in droplet concentration will alter the probability of insects contacting a droplet [20]. To compensate for this effect, two options are available. First, a sprayer that produces a similar droplet spectrum over a wide range of flow rates should be selected and future sprayer development efforts should incorporate this capability. Second, an effort should be directed toward finding a combination of flow rate and travel speed that does not

significantly impact the number of droplets produced per unit of flow rate. This might also lead to defining different application rates for different nozzle volume flow rates.

The mass flow rate has a strong relationship with droplet statistics of the truck-mounted ULV sprayer (Fig. 6). This suggests that it may be possible to use alternate fluids for droplet size characterization by adjusting flow rate of the selected fluid to match the mass flow rate of the test fluid. As an example a 100-ml/min flow rate of Fyfanon (density of 1.073 g/ml, Cheminova Inc., Wayne, NJ) can be replaced by 127 ml/min of BVA-13 (density of 0.845 g/ml). However, these characters must be evaluated on additional sprayers before it is recommended.

Results from hand-held thermal fogger testing revealed a decrease in all droplet size statistics, increase in droplet concentration and decrease in spray volume with increasing distance away from the fogger outlet (Table 3). Decrease in spray volume indicates an expected dispersion of spray material into a larger space as the fog moves away from the fogger. Change in droplet size could be because of droplets shrinking as they cool moving away from the outlet. However, the increase in droplet concentration is not understood with the information available. It can only be speculated that there is a secondary break up, may be by splitting of larger droplets to smaller ones, because of very rapid cooling of the droplets as they move away the fogger. This phenomenon seems to benefit in overall control efforts by making a larger number of smaller droplets available for insects to contact and increasing dispersion in lighter air movements. It would be particularly advantageous for those pesticides that can have lethal dose for insects even in these smaller droplets. However, this phenomenon should be further evaluated and studied.

It should be noted that physical properties of the spray formulation are known to affect droplet size characteristics produced by the sprayers [21,22]. In general, droplet size increases with an increase in viscosity and surface tension. Data from Hoffmann et al. [23] shows that $D_{V0.1}$ increases at a faster rate with increasing viscosity and surface tension compared to increase in $D_{V0.5}$ and $D_{V0.9}$. The majority of ULV spray formulations have physical properties similar to water (viscosity = 1.0 cP, surface tension = 73 mN/m [23]) or BVA-13 oil (viscosity = 17.1 cP, surface tension = 34 mN/m [23]) and the results reported in this study are expected to prevail for ULV formulations for vector control. However, caution should be exercised when applying these trends to other pesticide formulations having different physical properties.

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